AD-A016 537

PERFORMANCE OF THE PHILTRE PROCESSOR AT LOW SIGNAL-TO-NOISE RATIOS

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Teledyne Geotech

Prepared for:

Air Force Technical Applications Center

31 July 1975

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SDAC-TR-75-6	2. GOVT ACCESSION NO	3. RECIPIENT'S CATALOG NUMBER AD-A016 537
4. TITLE (and Subtitle) PERFORMANCE OF THE PHILTRE PROCESSOR AT LOW SIGNAL-TO-NOISE RATIOS		5. TYPE OF REPORT & PERIOD COVERED Technical
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Sobel, P. A. and von Seggern, D. H.		8. CONTRACT OR GRANT NUMBER(s) F08606-76-C-0004
9. PERFORMING ORGANIZATION NAME AND ADDRESS Teledyne Geotech 314 Montgomery Street Alexandria, Virginia 22314		10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS VT/6709
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Nuclear Monitoring Research Office 1400 Wilson Blvd., Arlington, Virginia 22209		12. REPORT DATE 31 July 1975
		13. NUMBER OF PAGES ~~46~~ 49
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) VELA Seismological Center 312 Montgomery Street Alexandria, Virginia 22314		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adaptive filter	Detection filter
Time-varying filter	Seismic surface-wave detection
Seismic data processing	Seismic threshold
Seismic surface-wave enhancement	Seismic noise suppression

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this report we show that a non-linear, adaptive processor called PHILTRE is useful in detecting long-period Rayleigh waves in various low signal-to-noise ratio situations: signals buried in noise at various levels, two signals mixed at various azimuths and relative amplitudes, and a suite of visually undetected signals at LASA, ALPA, and NORSAR from the Kurils-Kamchatka region.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

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PERFORMANCE OF THE PHILTRE PROCESSOR AT LOW SIGNAL-TO-NOISE RATIOS

SEISMIC DATA ANALYSIS CENTER REPORT NO.: SDAC-TR-75-6

AFTAC Project Authorization No.:	VELA T/6709/B/ETR
Project Title:	Seismic Data Analysis Center
ARPA Order No.:	2551
ARPA Program Code No.:	6F10
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F08606-76-C-0004
Date of Contract:	01 July 1975
Amount of Contract:	$2,319,926
Contract Expiration Date:	30 June 1976
Project Manager:	Royal A. Hartenberger (703) 836-3882

P. O. Box 334, Alexandria, Virginia 22314

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ABSTRACT

In this report we show that a non-linear, adaptive processor called PHILTRE is useful in detecting long-period Rayleigh waves in various low signal-to-noise ratio situations: signals buried in noise at various levels, two signals mixed at various azimuths and relative amplitudes, and a suite of visually undetected signals at LASA, ALPA, and NORSAR from the Kurils-Kamchatka region.

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INTRODUCTION

This report examines a non-linear adaptive processor, termed PHILTRE and described below, for long-period Rayleigh waves which are recorded in various low S/N ratio situations. One situation involves burying signals in noise at various levels, another involves mixing two signals at various azimuths and relative amplitudes, and a third involves a suite of visually undetected signals from the Kurils-Kamchatka region.

The time-varying, non-linear processor (termed PHILTRE) used to enhance long-period surface waves in this report was first presented by Simons (1968). This technique operates on all three traces after rotating the horizontal traces to be radial and transverse to the great-circle path from epicenter to station. The traces are first transformed to the frequency domain. Then the frequency components are weighted according to: 1) apparent azimuth of approach relative to the expected azimuth and 2) closeness of observed phase lag between vertical and radial traces to the expected 90° for Rayleigh waves. Finally the weighted harmonic components are inverse transformed to produce the output. Evaluations of this type of processor have been made by Choy and McCamy (1973) and Nelson and von Seggern (1974) using digital recordings from the VLPE network. Results shown in these studies as well as Simons' paper were encouraging; however, since most of the signals in these studies were visually detectable anyway before application of the processor, a stringent test of the processor's capability at very low S/N ratios has not been provided. Such a test, presented in this report, is necessary because the non-linear nature of the processor should cause its efficacy to deteriorate rapidly below S/N ratios of one.

Simons, R., 1968, PHILTRE - A surface wave particle motion discrimination process, Bull. Seism. Soc. Am., v. 58, p. 629-637.

Choy, G. and K. McCamy, 1973, Enhancement of long-period signals by time varying adaptive filters, J. Geophys. Res., v. 78, p. 3505-3511.

Nelson, D. and von Seggern, D. H., 1974, Signal enhancement of LPE data, SDAC-TR-73-4, Teledyne Geotech, Alexandria, Virginia.

SIGNAL ENHANCEMENT OF LPE DATA FOR EVENTS MIXED WITH VARIOUS NOISE SAMPLES

Procedure

For this part of the study we selected one event and three noise samples from two LPE sites: CTA (Charters Towers, Australia) and KIP (Kipapa, Hawaii). The coordinates of the stations and events and the times of the event samples are shown in Tables I and II. The noise samples are from the first 9 days of June 1972. The frequency response of the LPE system is centered at approximately 40 seconds period. Seismic data are digitally recorded at the sites with a sampling interval of one second.

The input traces are initially bandpass filtered for periods between approximately 12 and 80 seconds. A six-minute section of the LR phase having maximum amplitude is mixed at various magnifications with each of the three noise samples at that station. Then the mixed traces are processed through the program PHILTRE.

Results

Figures 1 through 6 are 30-minute plots of some of the mixed traces. Each figure shows 6 traces: traces 1-3 are input traces to PHILTRE, bandpass filtered and rotated into vertical, radial, and transverse components, and traces 4-6 are PHILTRE outputs. Although gains are equalized between the three components for computation, they are not equalized on the plots where the traces are plotted so that the maximum amplitudes are the same height on each trace. The amplifications to the right of each processed trace are correct only with respect to one another; they give a measure of the relative amplitude of the horizontal traces to the vertical traces. If it were desired to calculate M_s at e.g. 20 seconds from these plots it would be necessary to multiply the Z component time series by a constant equal to the inverse of the 20-second PHILTRE coefficient. Where there is a small amplitude output, the output traces show spikes and sudden jumps.

To generate Figure 7 which shows S/N output as a function of S/N input we first imbedded signals in noise at high S/N values. The S/N values were then

TABLE I

Parameters for Events Buried in Noise

Event	Origin Time	Coordinates	m_b	Depth	Δ	Θ	Location
CTA	04 Jun 72 - 102458	0.6S 67.4E	4.9	33	79	273	Carlsberg Ridge
KIP	02 Jun 72 - 214647	51.8N 174.6W	4.9	50	33	341	Andreanof Is. Aleutians

TABLE II

LPE Station Parameters

Station	Coordinates
CTA	20.1S 146.3E
KIP	21.4N 158.0W

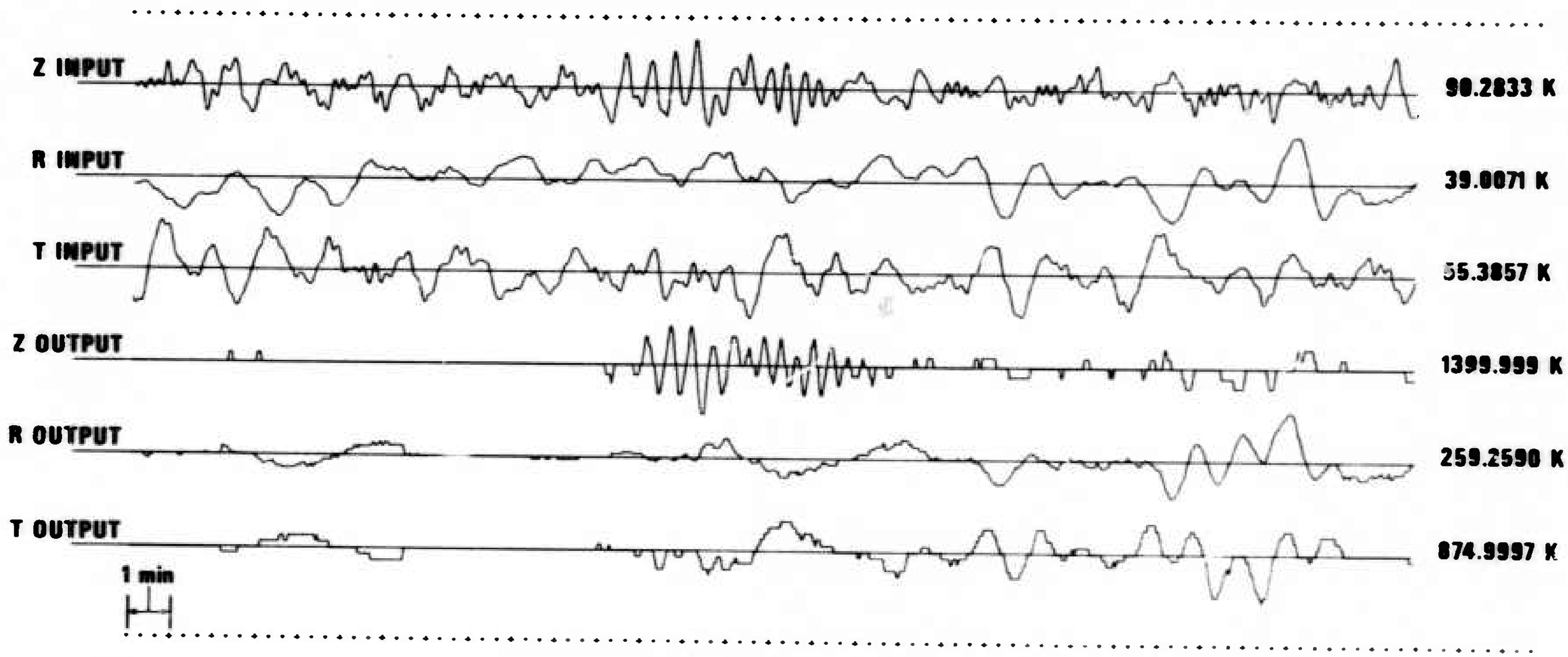

Figure 1. Signal at station CTA mixed with first noise sample (C1). $S/N_{in}=-2dB$. $S/N_{out}=16.8dB$.

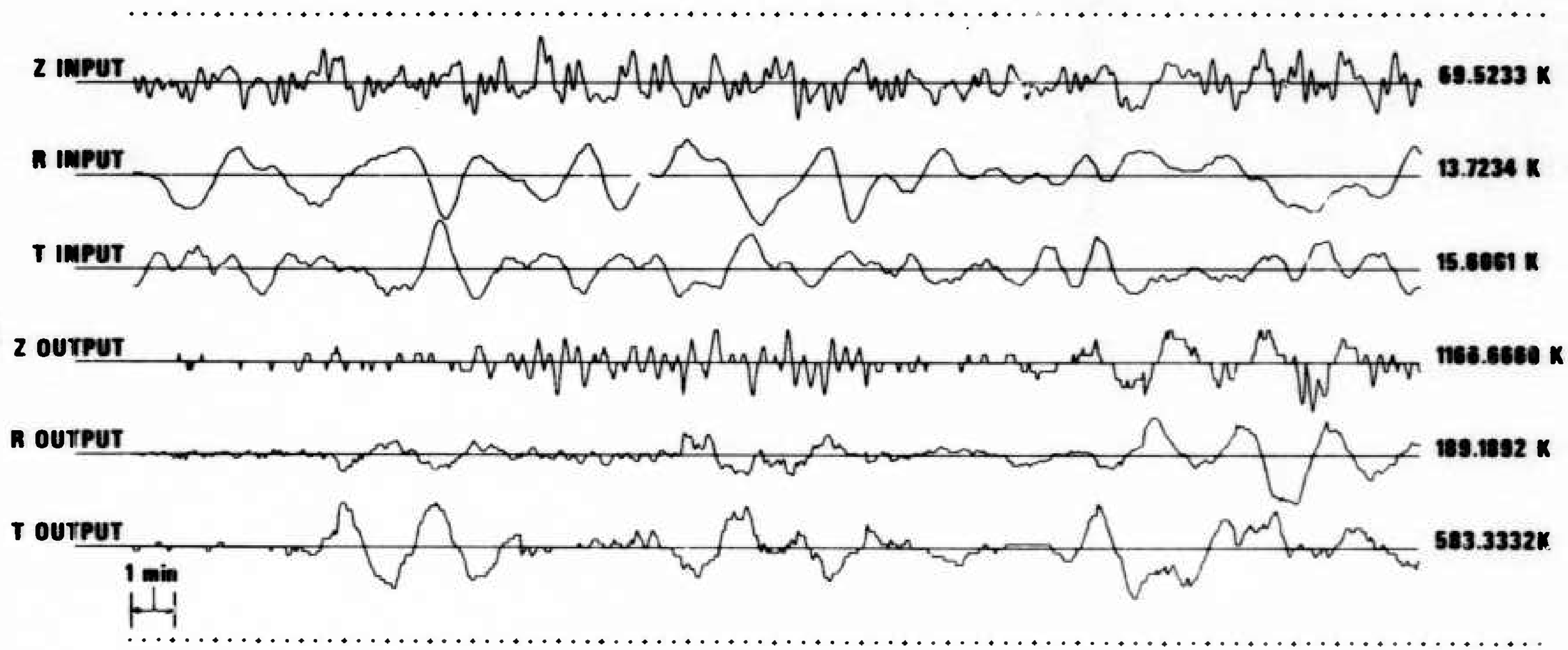

Figure 2. Signal at station CTA mixed with second noise sample (C2). S/N_{in}=-16.4dB. S/N_{out}=10.4dB.

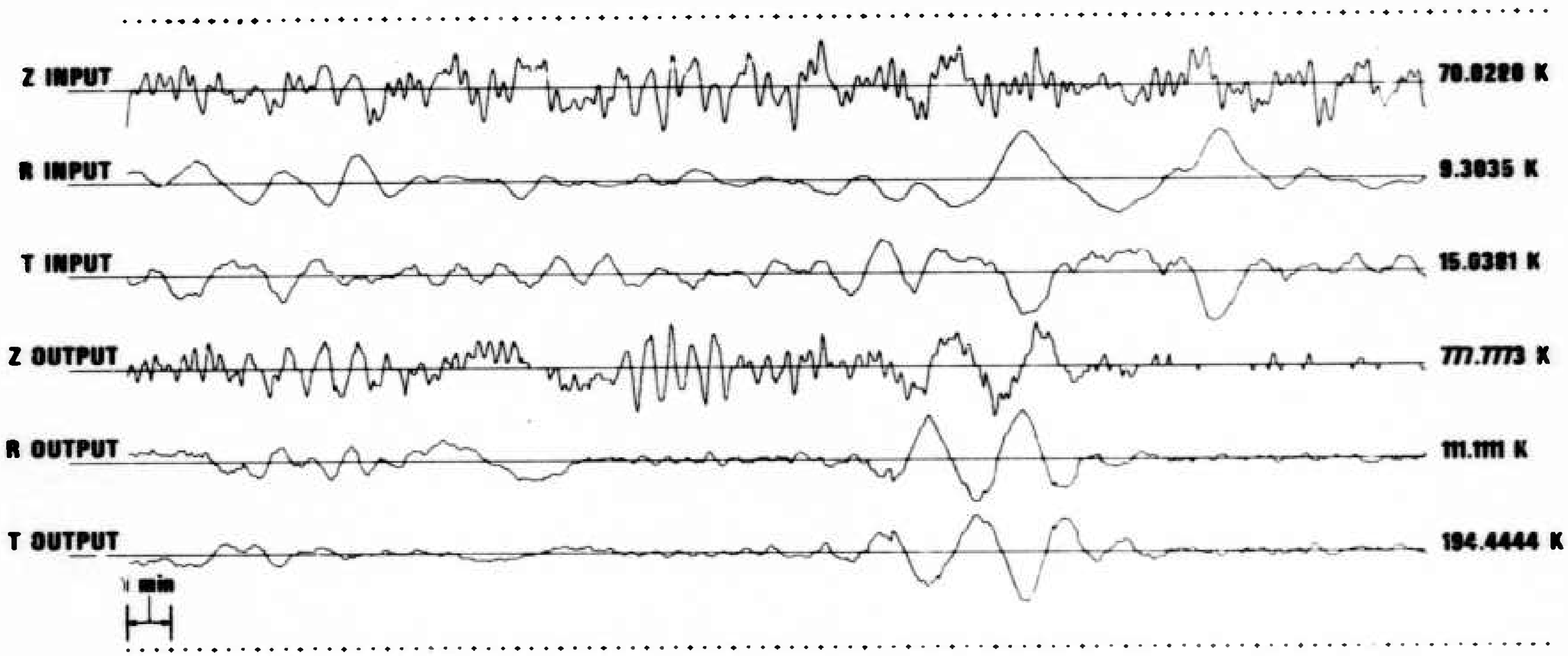

Figure 3. Signal at station CTA mixed with third noise sample (C3).
S/N_{in}=-2.0dB. S/N_{out}=1.0dB.

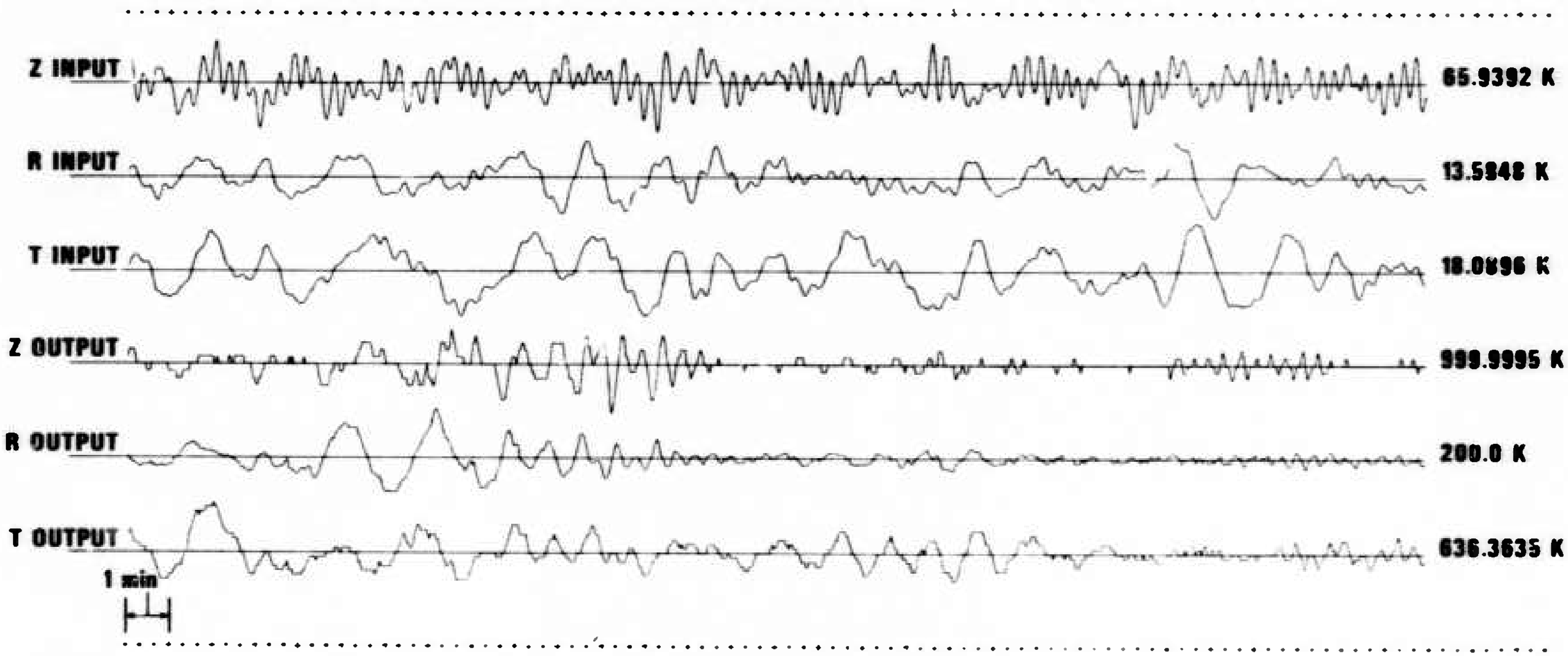

Figure 4. Signal at station KIP mixed with first noise sample (K1). S/N_{in}=-6.8dB. S/N_{out}=3.9dB.

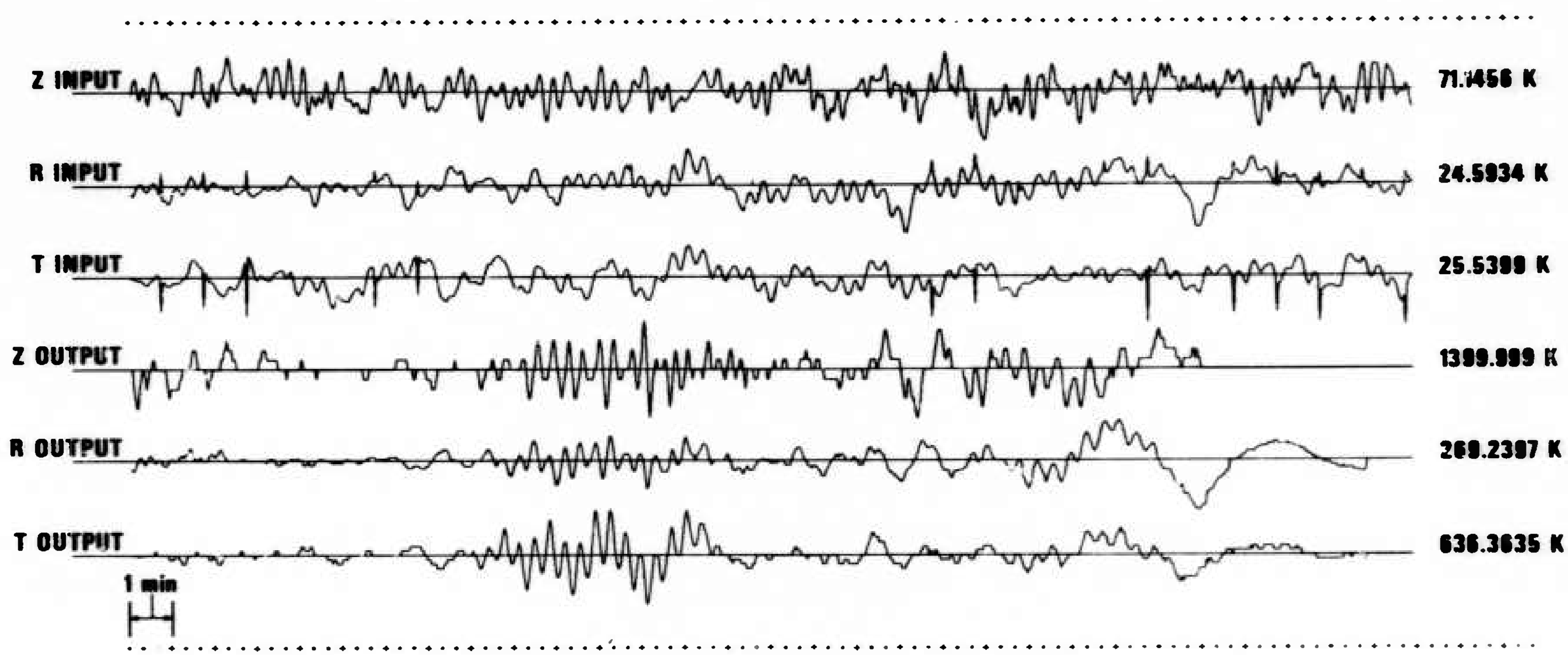

Figure 5. Signal at station KIP mixed with second noise sample (K2). S/N_{in}=-15.9dB. S/N_{out}=3.0dB.

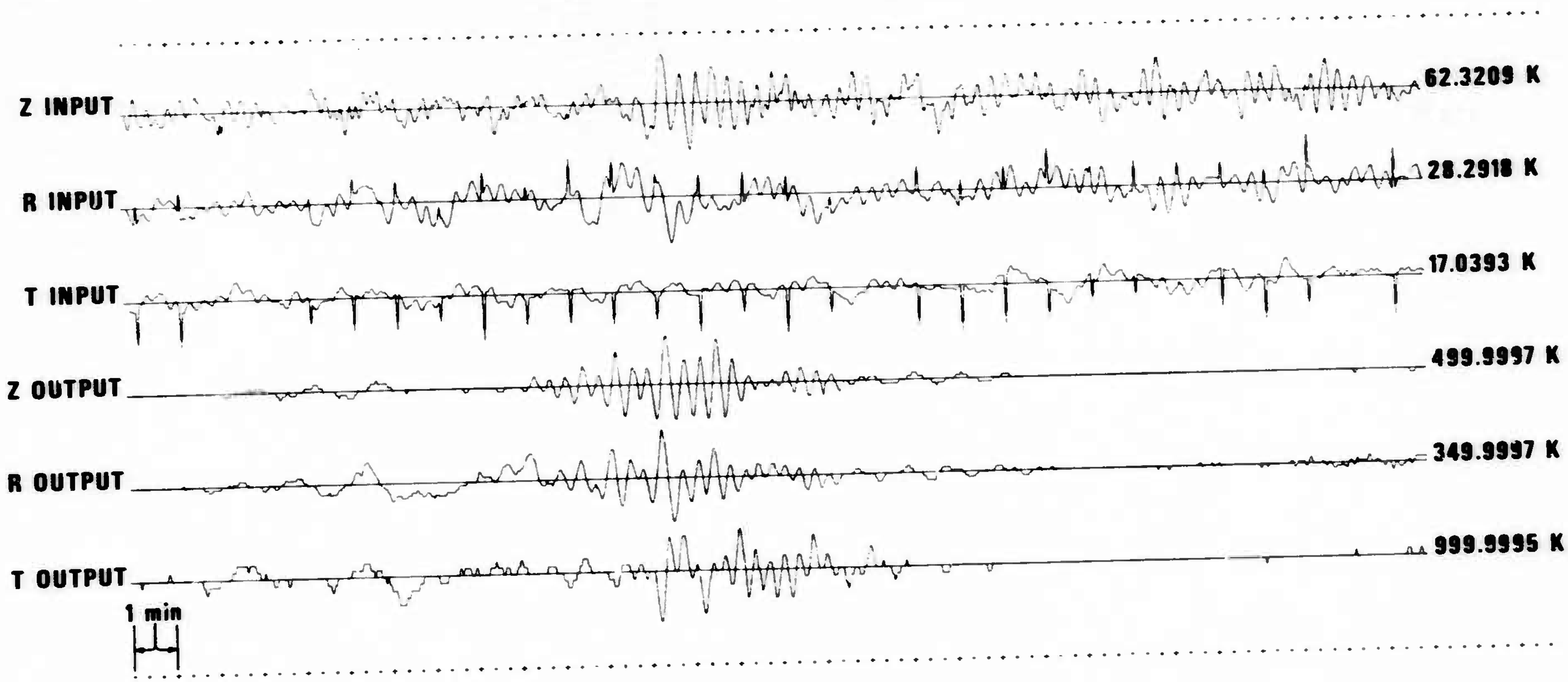

Figure 6. Signal at station KIP mixed with third noise sample (K3). S N_{in}=3.5dB. S/N_{out}=16.1dB.

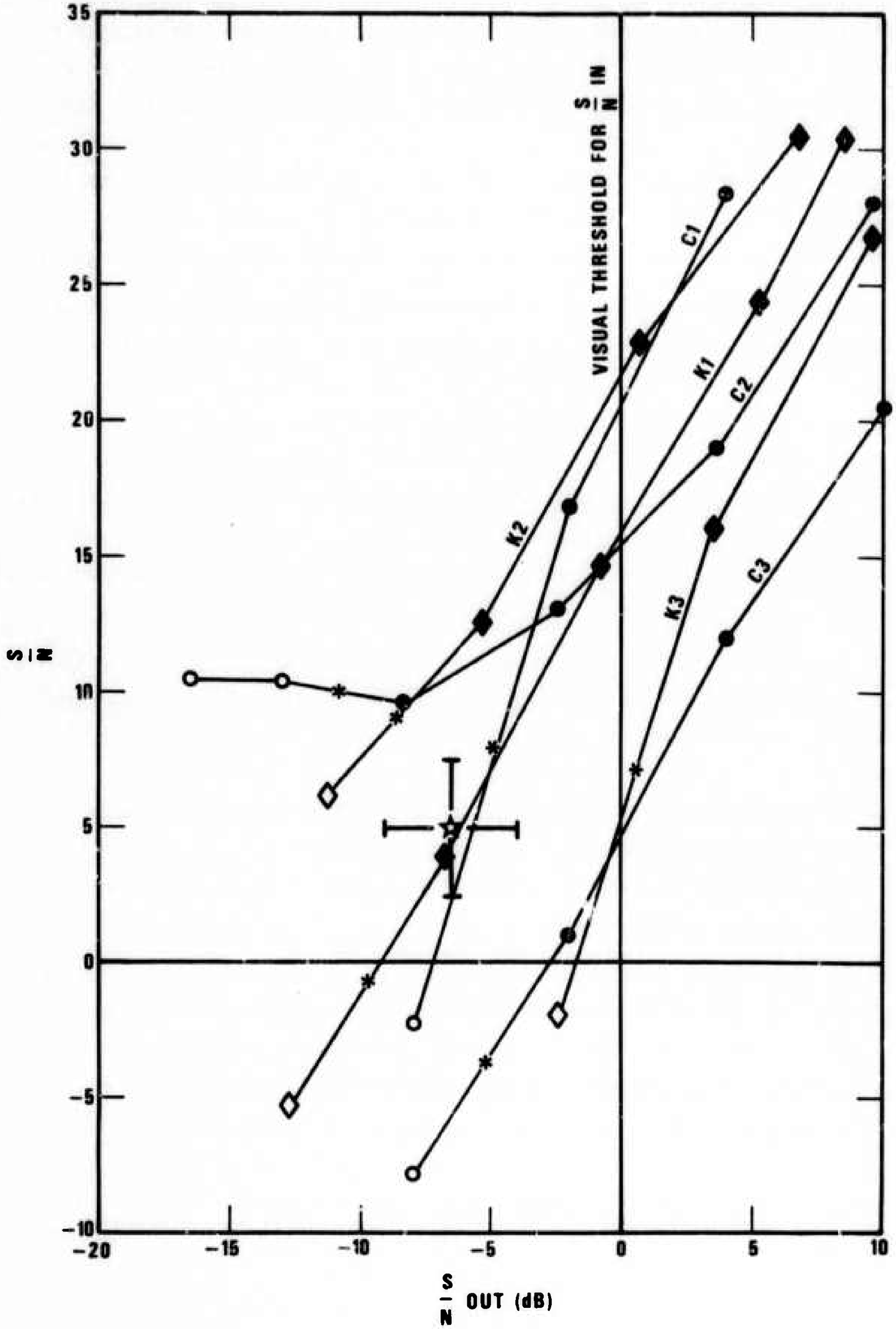

Figure 7. PHILTRE S/N Improvement. S/N_{in} vs. S/N_{out}.

defined as the maximum peak-to-trough signal amplitude divided by six times the rms noise amplitude for the noise alone in the first 256-second window on the plot. Successive traces were generated by adding the signal to the noise with increasingly smaller signal amplitudes. The S/N values for these traces were calculated by scaling the S/N values in proportion to the signal amplitude since it would be impossible to empirically measure S/N input for those cases where the mixed signal falls below the visual threshold on input.

Examination of Figure 7 shows that the mean processor gain is 14 dB at the visual threshold which is at a S/N input of 1.0, which corresponds roughly to an empirical 50% M_s threshold (von Seggern, 1975). The curves in Figure 7 are plotted for successively lower S/N input until, in the analyst's judgment, the signal cannot be detected on the processed traces. (The filled symbols denote detections and the empty symbols denote those cases where the signal was not detected.) The asterisks plotted in Figure 7 are midway between the last detection and first non-detection and are the estimated points at which the signal would be detected with 50% probability.

The star in Figure 7 gives the mean of the 50% detection points. Although the standard deviation of the mean seems quite large, the result is in agreement with other results to be presented below. We see that the detection threshold for S/N inputs has been reduced approximately 6 dB. However, at this detection threshold, the S/N output is not 0 dB; it is approximately 5 dB. The 5 dB of improvement is due to the non-linearity of the processor and to noise pulses in the signal window. As we have seen, if S/N inputs are reduced further the analyst cannot see the signal.

Thus the processor promises a decrease in the M_s detection threshold of approximately 0.3 units. This result, if achievable in routine applications, is comparable to those for other processors, such as matched filtering and multichannel filtering. There is the possibility that PHILTRE could be applied to the output of such processors resulting in larger additive gain.

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von Seggern, D. H., 1975, Final report on the analysis of recordings from the Very Long Period Experimental stations, Teledyne Geotech, Alexandria, Virginia.

SIGNAL SEPARATION OF EVENTS RECORDED AT LPE SITES

Procedure

In this section we examine the ability of PHILTRE to recover a signal when another signal is present. As explained in the introduction, PHILTRE weights the frequency components of the trace according to deviation from expected azimuth. From 0 to 90 degrees from the expected azimuth, the frequency components are weighted according to the fourth power of the cosine of the expected azimuth minus the calculated direction of motion. For calculated directions between 90 and 180 degrees from the expected azimuth, the frequency components are multiplied by zero.

To study PHILTRE's capability in the presence of interference, two signals were chosen from LPE recordings at the site CTA and two from KIP. Table III lists the coordinates of the events with which the signals were associated and the times of all samples.

A four-to-five minute, maximum-amplitude section of the LR phase for the second event recorded at each site is mixed at various lags, magnifications, and azimuthal separations with the first event. Then the mixed traces are rotated to the back azimuth of the second signal and processed through PHILTRE in an attempt to detect the second signal.

Results

Figures 8 through 11 are 30- minute plots of the four signals before mixing. The signals have been processed through PHILTRE, and these PHILTRE outputs should be compared with examples of PHILTRE outputs of the mixed traces shown in Figures 12 through 15. Figures 16 and 17 summarize detection results for all the cases using the relative amplitudes of the first and second signals versus their azimuthal separation for lags of 1 minute and 2 minutes between the two phases, respectively. A lag of 2 minutes represents about one-half overlap of the phases and a lag of 1 minute is about three-quarters overlap of the LR phases. The second signal was defined to be detected if its amplitude was at least twice that of the first signal.

TABLE III

Parameters for Events used in Mixing

Event	Origin Time	Coordinates	m_b	Depth	Δ	Θ	Location
CTA-1	04 Jun 72 - 102458	0.6S 67.4E	4.9	33	79	273	Carlsberg Ridge
CTA-2	06 Jun 72 - 195558	16.3S 173.3W	4.8	33	39	91	Tonga Islands
KIP-1	02 Jun 72 - 214647	51.8N 174.6W	4.9	50	33	341	Andreanof Islands Aleutians
KIP-2	06 Jun 72 - 120801	34.0N 45.9W	3.9	33	96	49	North Atlantic Ridge

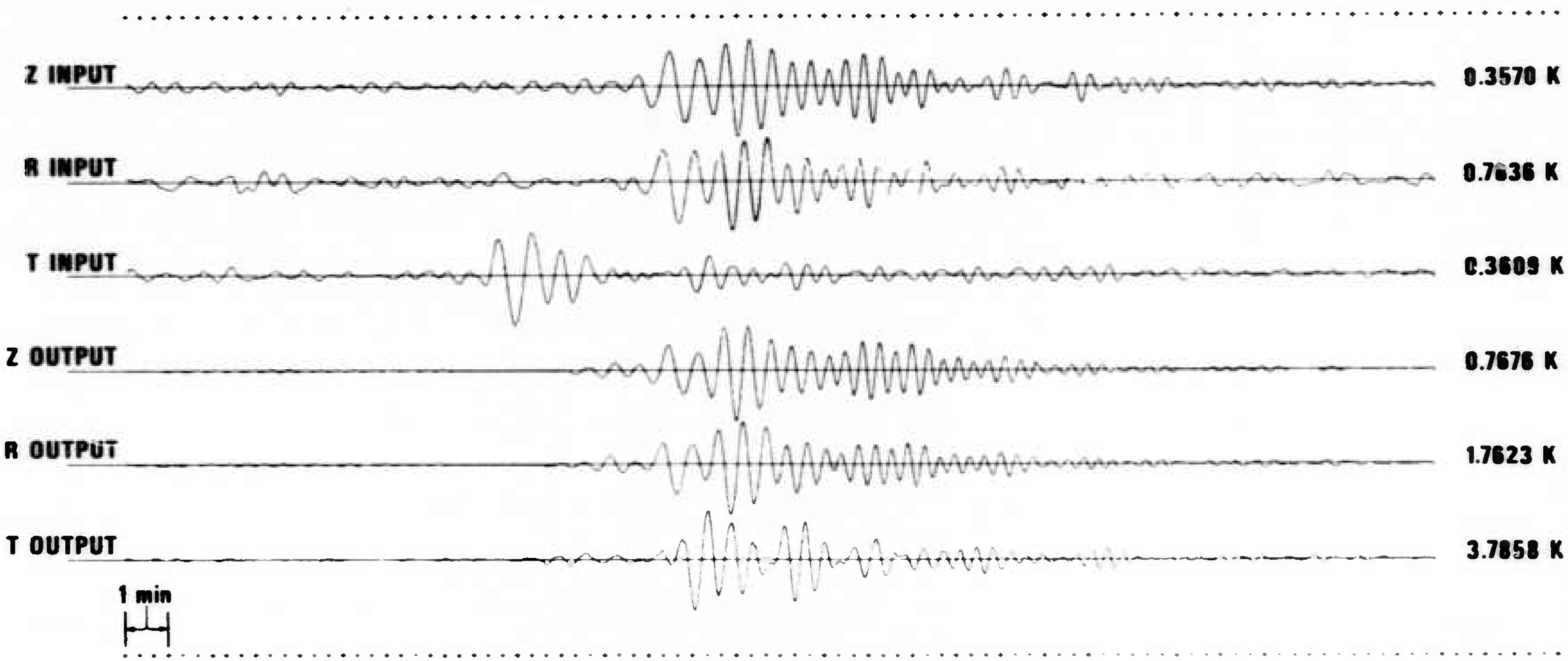

Figure 8. Signal CTA1. S/N_{in}=14.0dB. S/N_{out}=30.3dB.

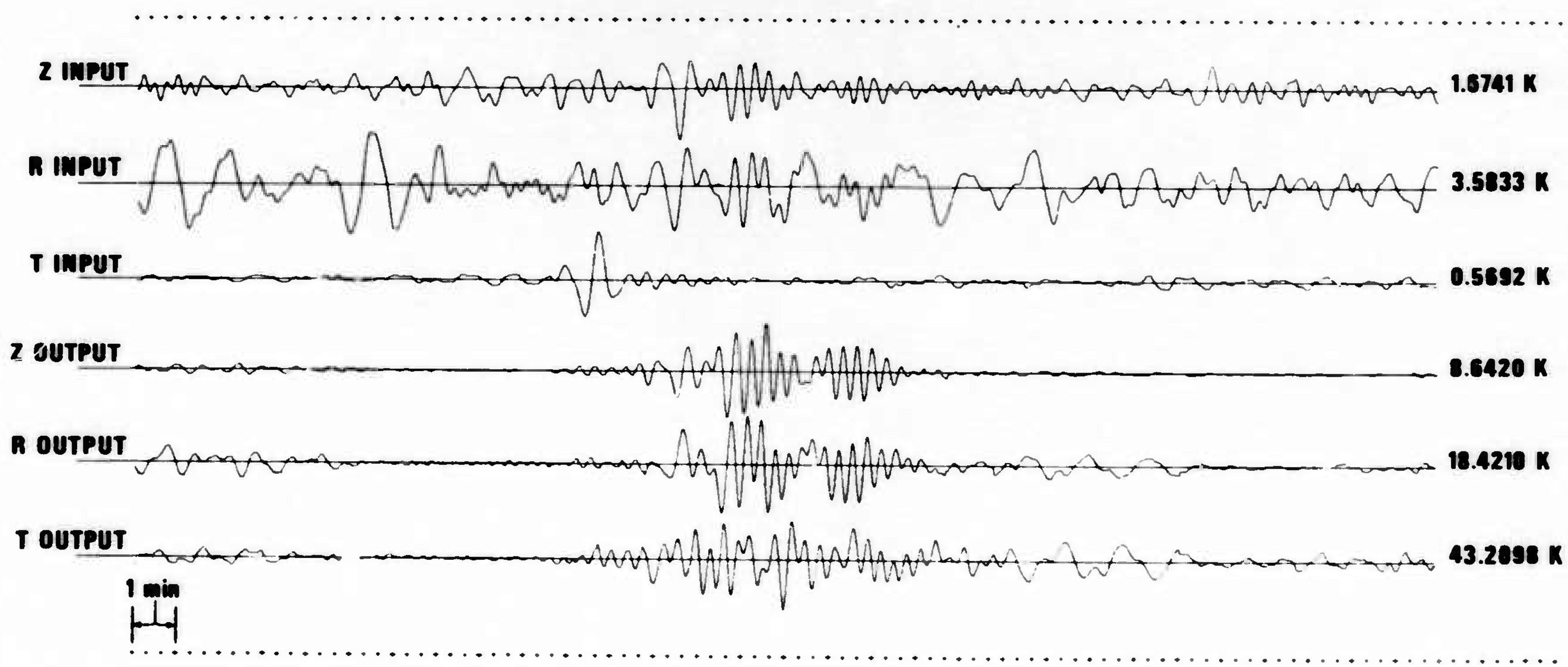

Figure 9. Signal CTA2. S/N_{in}=7.1dB. S/N_{out}=15.8dB.

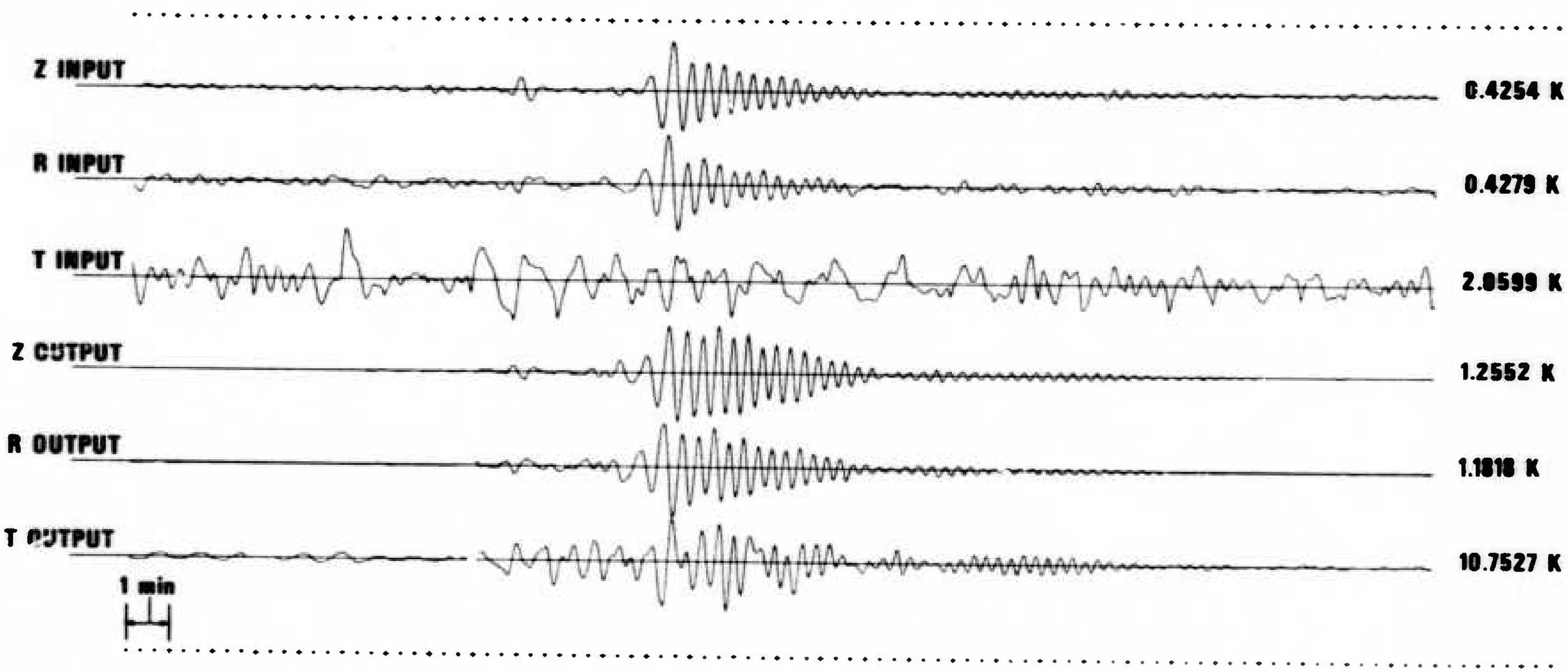

Figure 10. Signal KIP1. S/N_{in}=21.3dB. S/N_{out}=45.dB.

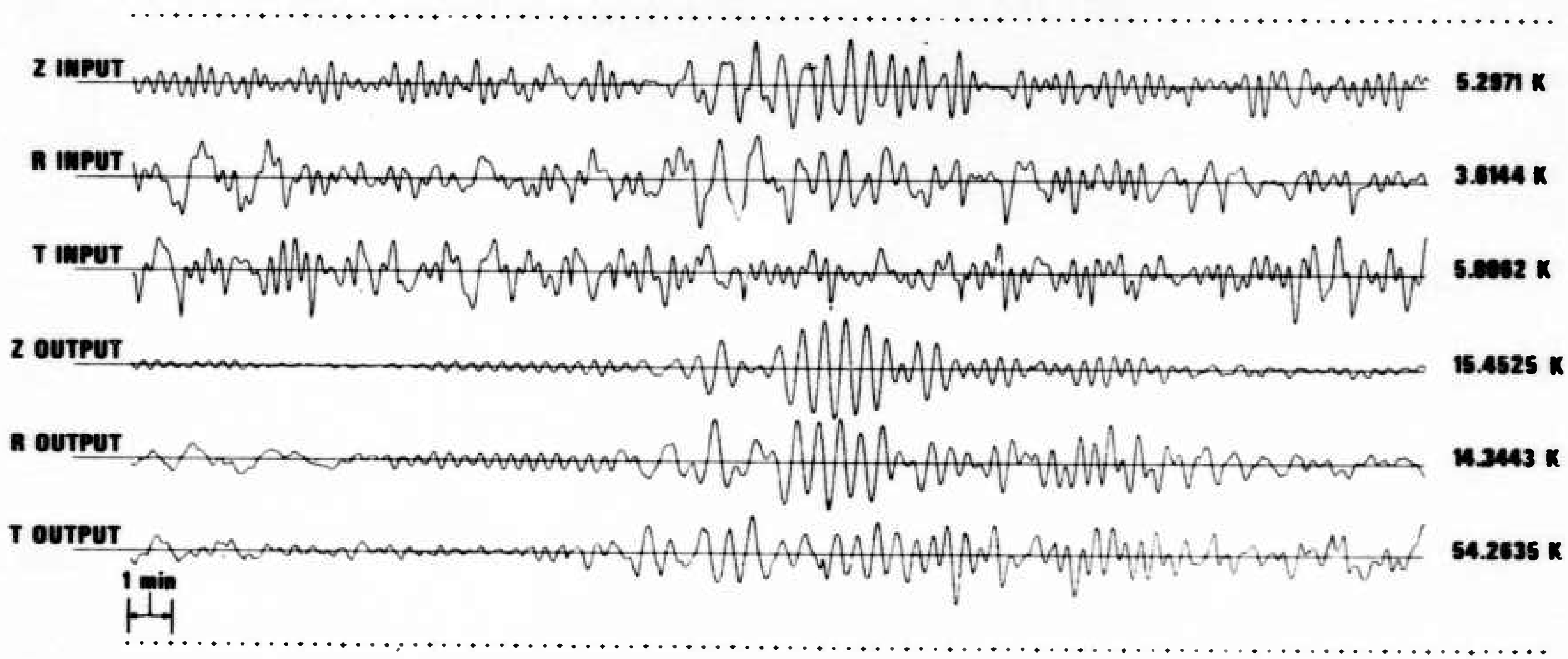

Figure 11. Signal KIP2. S/N_{in}=4.4dB. S/N_{out}=17.6dB.

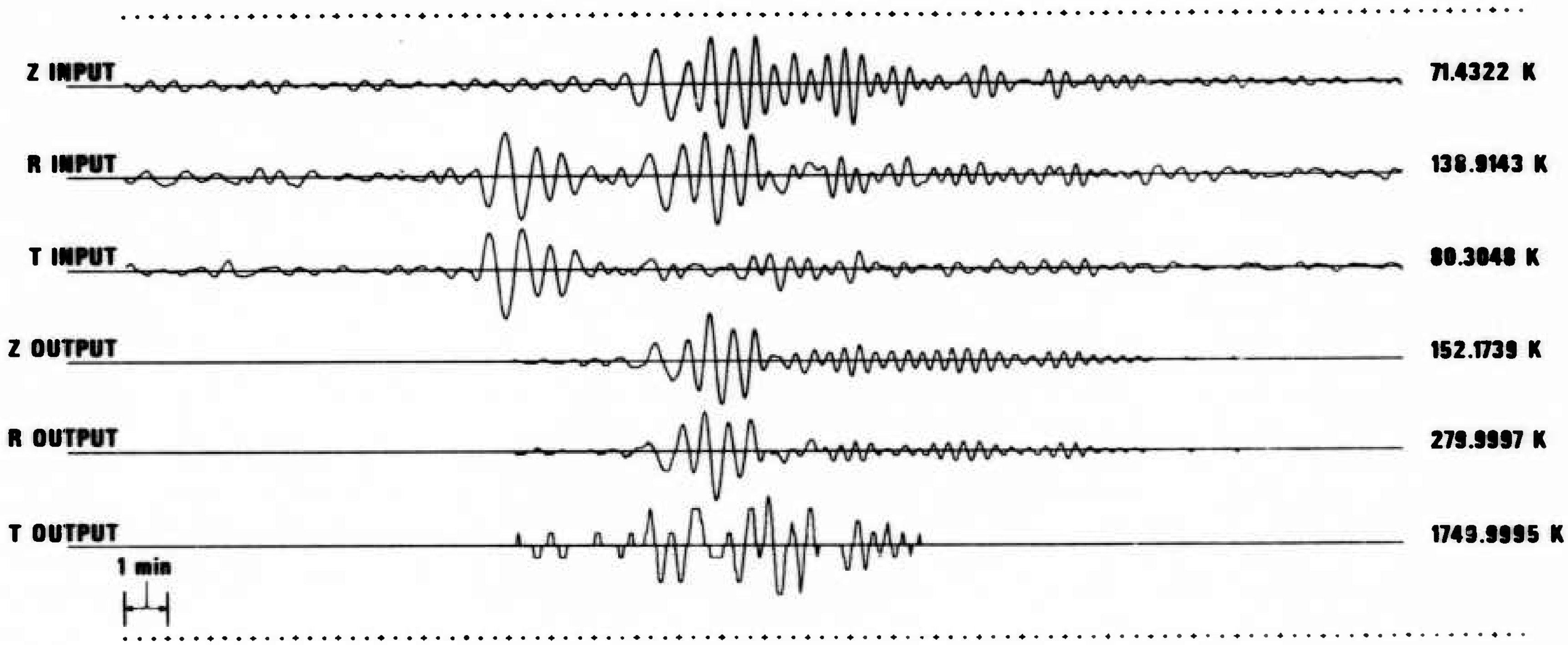

Figure 12. Mixing of two signals at station CTA, showing marginal separation of second signal. Lag=1 minute. Azimuthal separation = 30°. Amplitude of second signal = 40% of first signal.

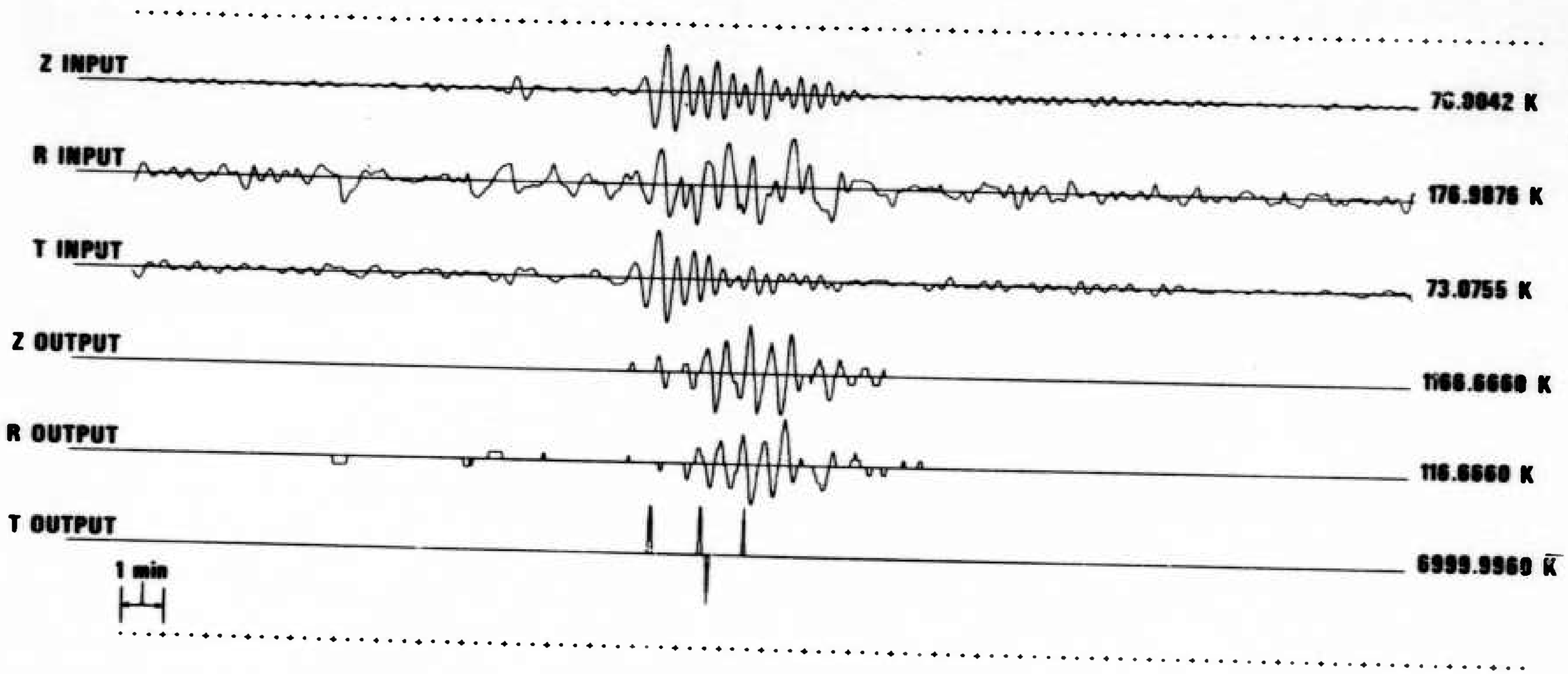

Figure 13. Mixing of two signals at station KIP, showing separation of second signal. Lag=1 minute. Azimuthal separation = 30°. Amplitude of second signal = 30% of first signal.

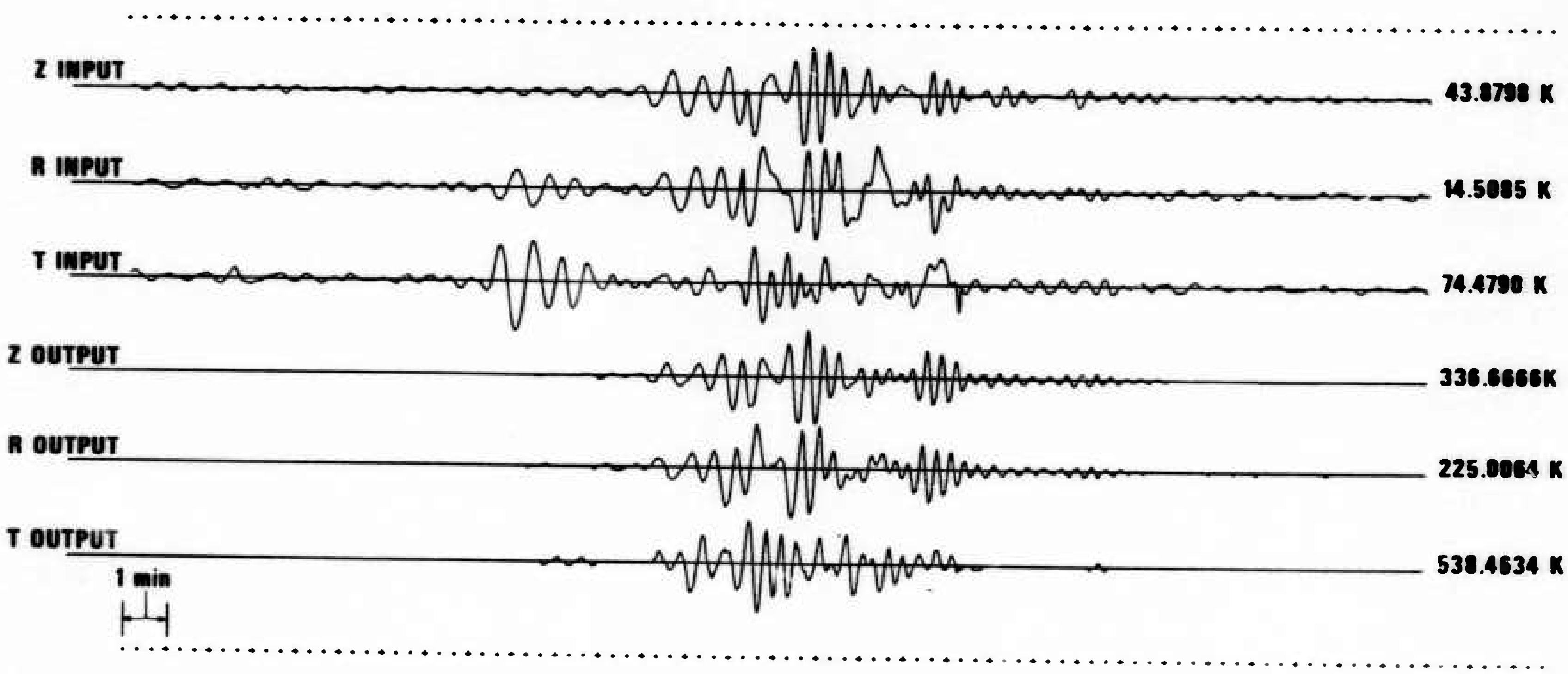

Figure 14. Mixing of two signals at station CTA, showing no additional separation of second signal. Lag=2 minutes. Azimuthal separation = 80°. Amplitude of second signal = 200% of first signal.

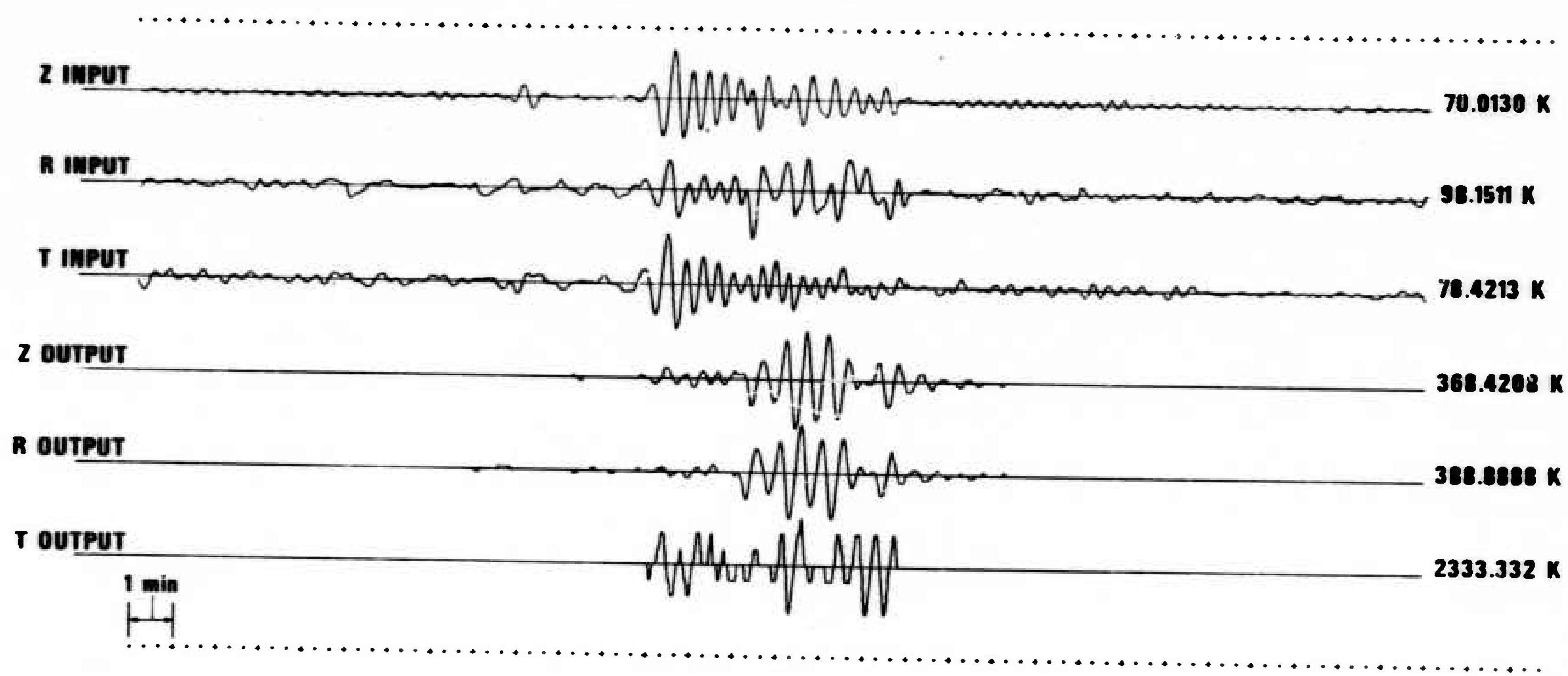

Figure 15. Mixing of two signals at station KIP, showing separation of second signal. Lag=2 minutes. Azimuthal separation = 70°. Amplitude of second signal = 50% of first signal.

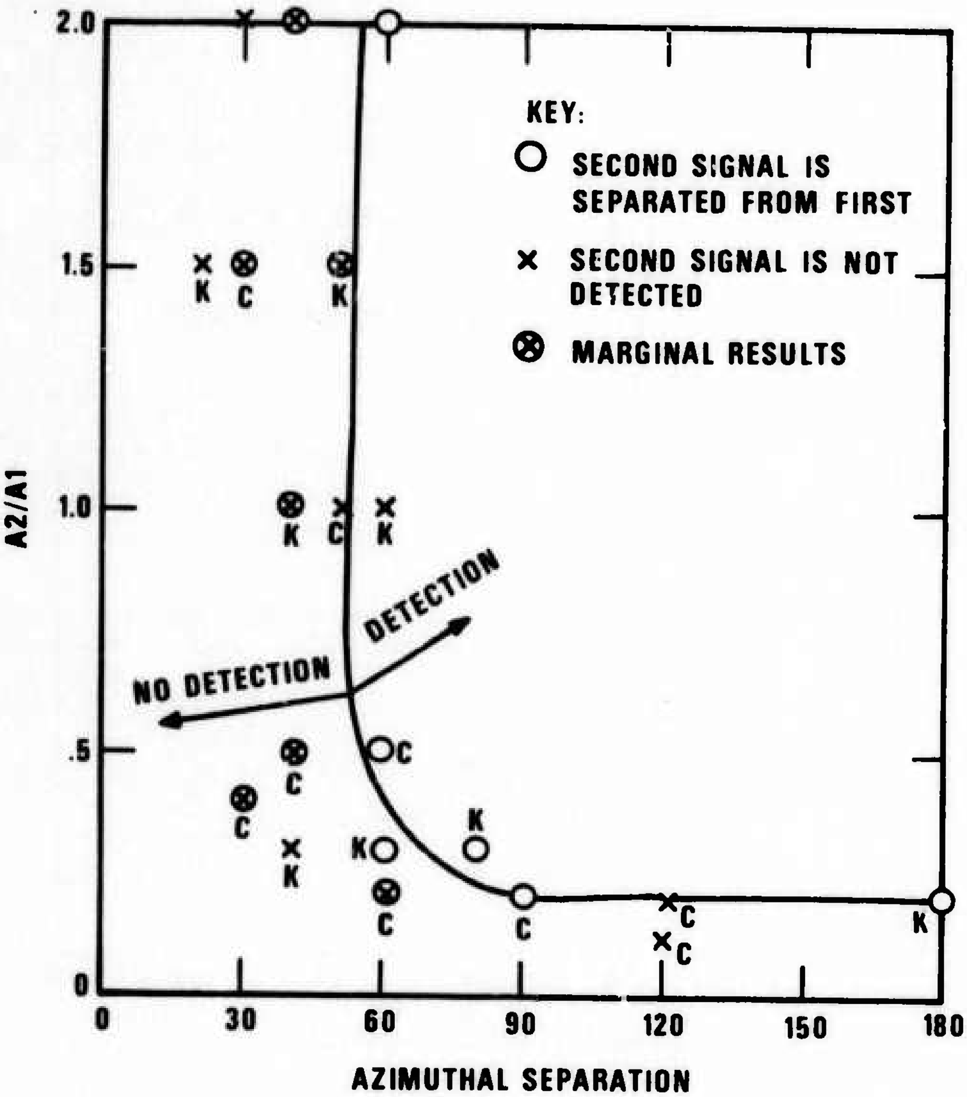

Figure 16. Relative amplitude vs. azimuthal separation for lag = 1 minute.

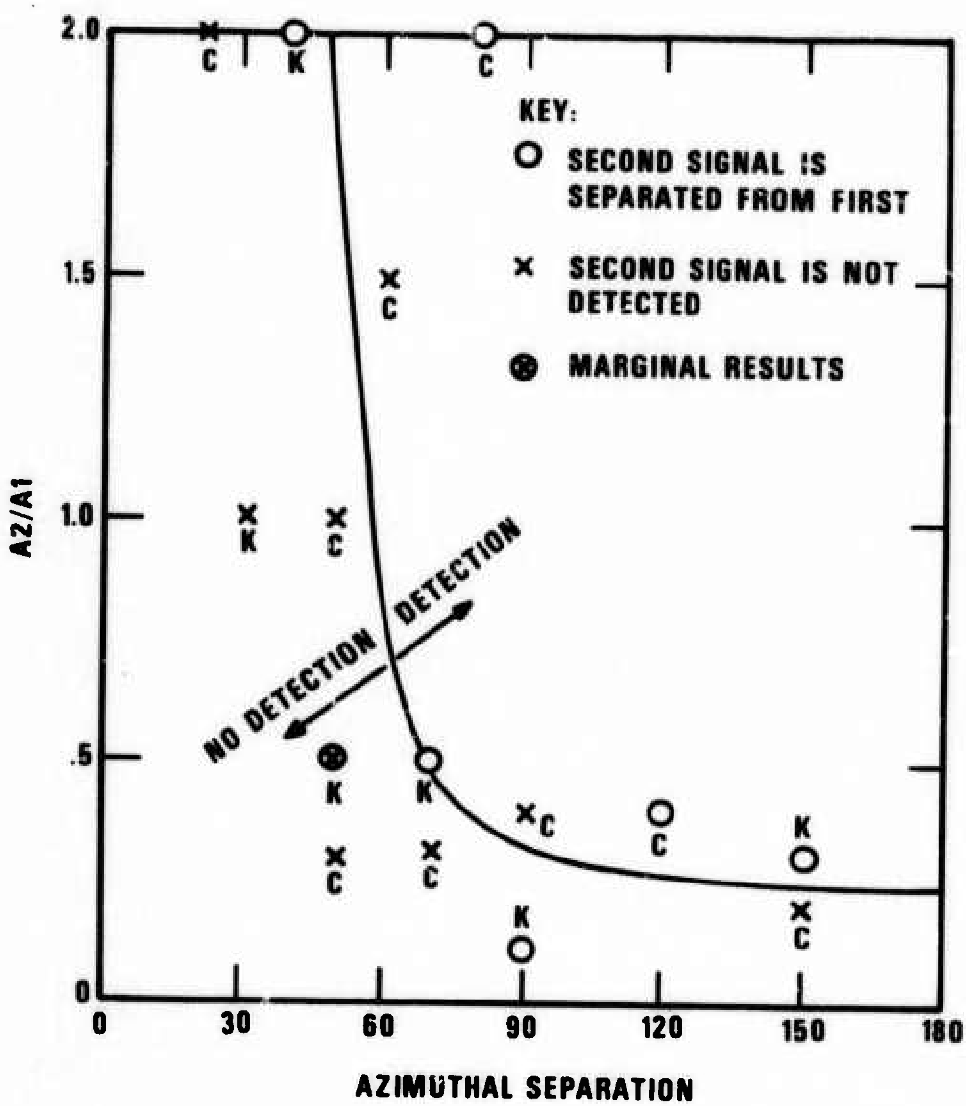

Figure 17. Relative amplitude vs. azimuthal separation for lag = 2 minutes.

At azimuthal separations of less than about 60 degrees, the second signal is not separated from the first signal unless the second signal was originally at least twice the amplitude of the first signal. The second signal is also not detected when it is less than about 20 percent of the amplitude of the first signal even when the azimuthal separation is greater than about 60 degrees. Above 20 percent of the amplitude of the first signal and for more than 60 degrees of azimuthal separation, the second signal is detected while the first signal is suppressed. These results demonstrate the usefulness of PHILTRE in those cases where masking of signals occurs; in the special case that the "noise" is actually another signal, PHILTRE can suppress the "noise" considerably if its azimuth is quite different and thereby recover signals well below the instantaneous "noise" level.

THRESHOLD IMPROVEMENT USING PHILTRE

Procedure

Long-period LR beams at the arrays ALPA, LASA, and NORSAR for events from the Kamchatka-Kurils, Seismic Region 19, in February and March 1972 have been formed and visually analyzed at the SDAC. Eighty-seven percent (87%) of the possible events were undetected visually on the beams at one or more arrays. (Masking contributed to this high rate of non-detection, as well as the signals being below ambient noise levels.) In order to estimate how much PHILTRE could lower the detection threshold, all beams were processed where the signal was masked or was simply undetected. To demonstrate the effectiveness of PHILTRE alone, no bandpass filter was used in the PHILTRE runs for these cases. Outputs from PHILTRE were submitted to the same analyst who originally read the unprocessed beams, and he decided whether the LR phase was not detected. In addition, all of the NORSAR data was simply band-pass filtered, using frequency cutoffs of .03 and .06 hertz, and showed no new detections; thus we concluded that any improvement by PHILTRE over raw traces would also be an improvement relative to band-pass filtering of the raw traces.

Results

Figures 18, 19, and 20 are samples of filtered outputs. Figures 21, 22, and 23 show the percentage of detection of LR versus bodywave magnitude for ALPA, LASA, and NORSAR data individually. Crosses denote the detection rates from visual beam analysis, and circles represent the rates after the beams having no detection or masking were processed through PHILTRE and rechecked by the same analyst. Normal distribution curves were fitted by computer through each set of data to demonstrate the shift in m_b detection thresholds before and after PHILTRE was applied to the data. Figures 24 and 25 show the 3-array network detection rates for at least 1 and 2 detections. Table VI shows the 50 percent m_b detection threshold from each normal curve. Although insufficient data results in rather wide confidence intervals on these values, the processing results generally show improvement in the threshold of detection. Considering all events, there is a 50 percent increase in the number of ALPA detections, a 61 percent increase in the number of LASA detections,

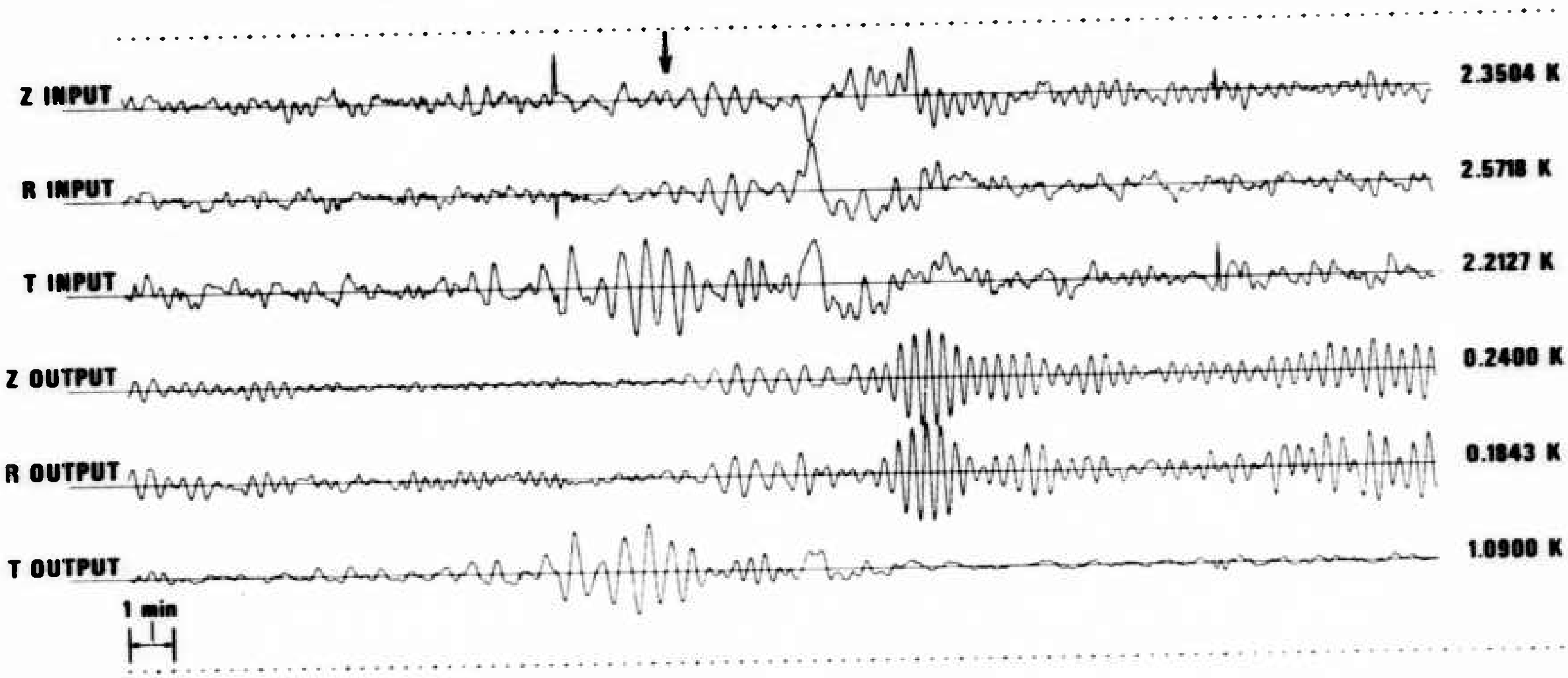

Figure 18. Undetected event at ALPA processed by PHILTRE. Arrow indicates expected arrival time of LR20. (Origin Time - 02:16:10.0. Epicenter - 40.9N, 141.9E, 4.3m_b.) Detection in output.

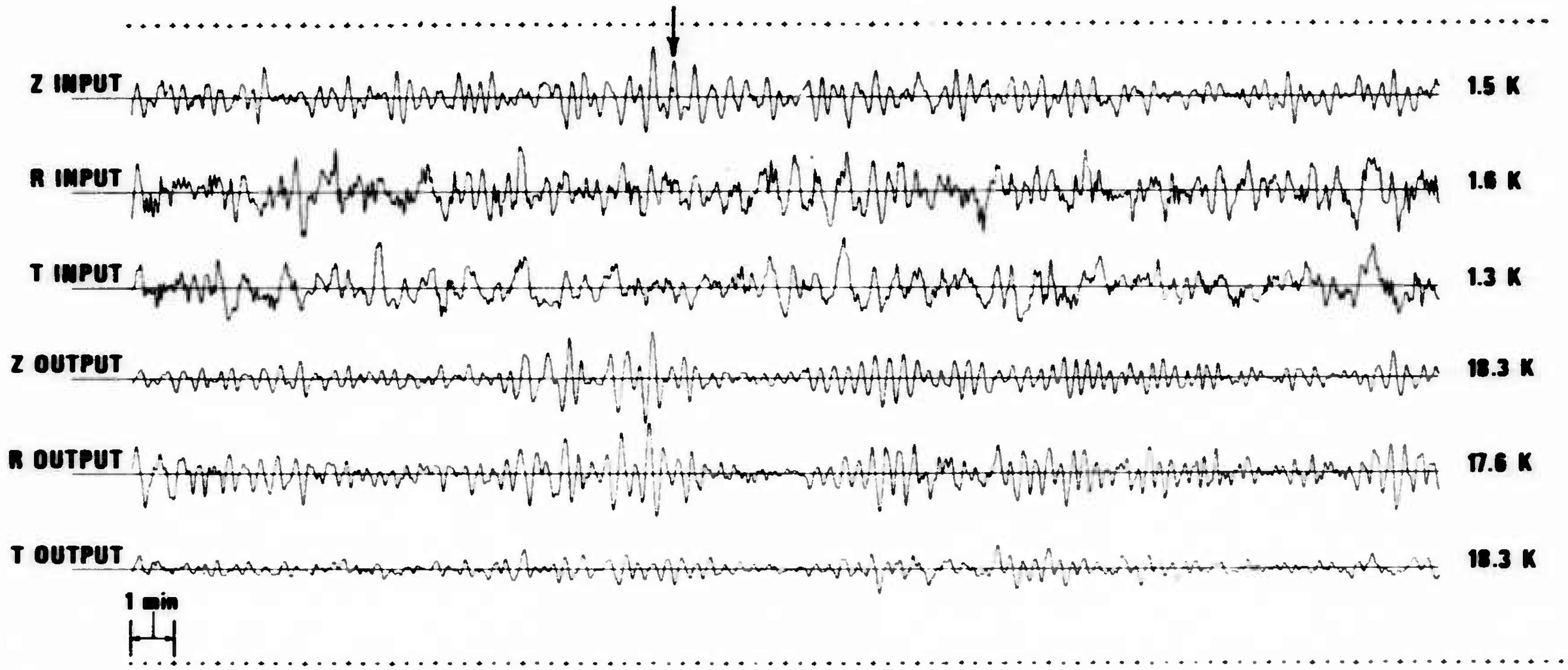

Figure 19. Undetected event at LASA processed by PHILTRE. Arrow indicates expected arrival time of LR20. (Origin Time - 04:06:25.9. Epicenter - 33.5N, 141.1E, 4.2m_b.) Detection in output.

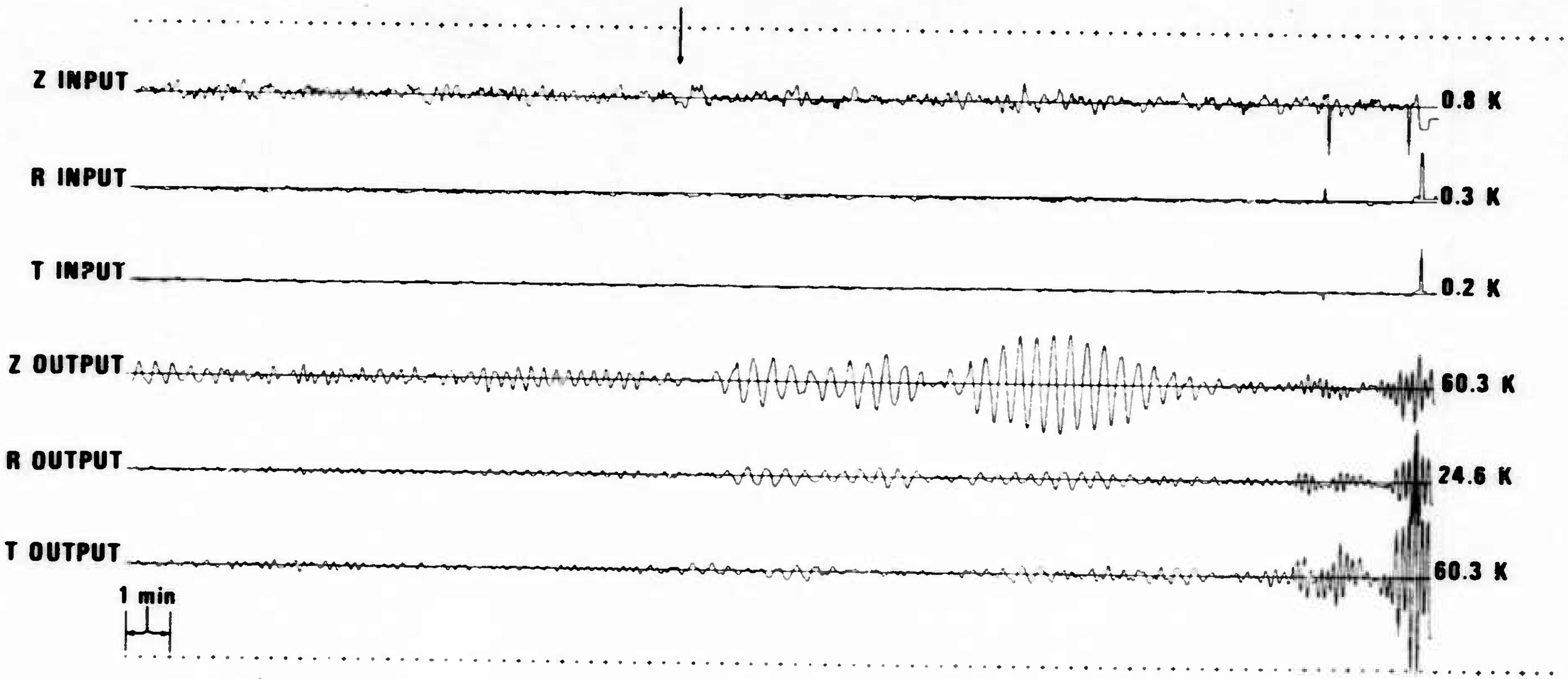

Figure 20. Undetected event at NORSAR processed by PHILTRE. Arrow indicates expected arrival time of LR20. (Origin time - 13:11:29.4. Epicenter - 40.1N, 142.3E, 3.8 m_b.) Detection in output.

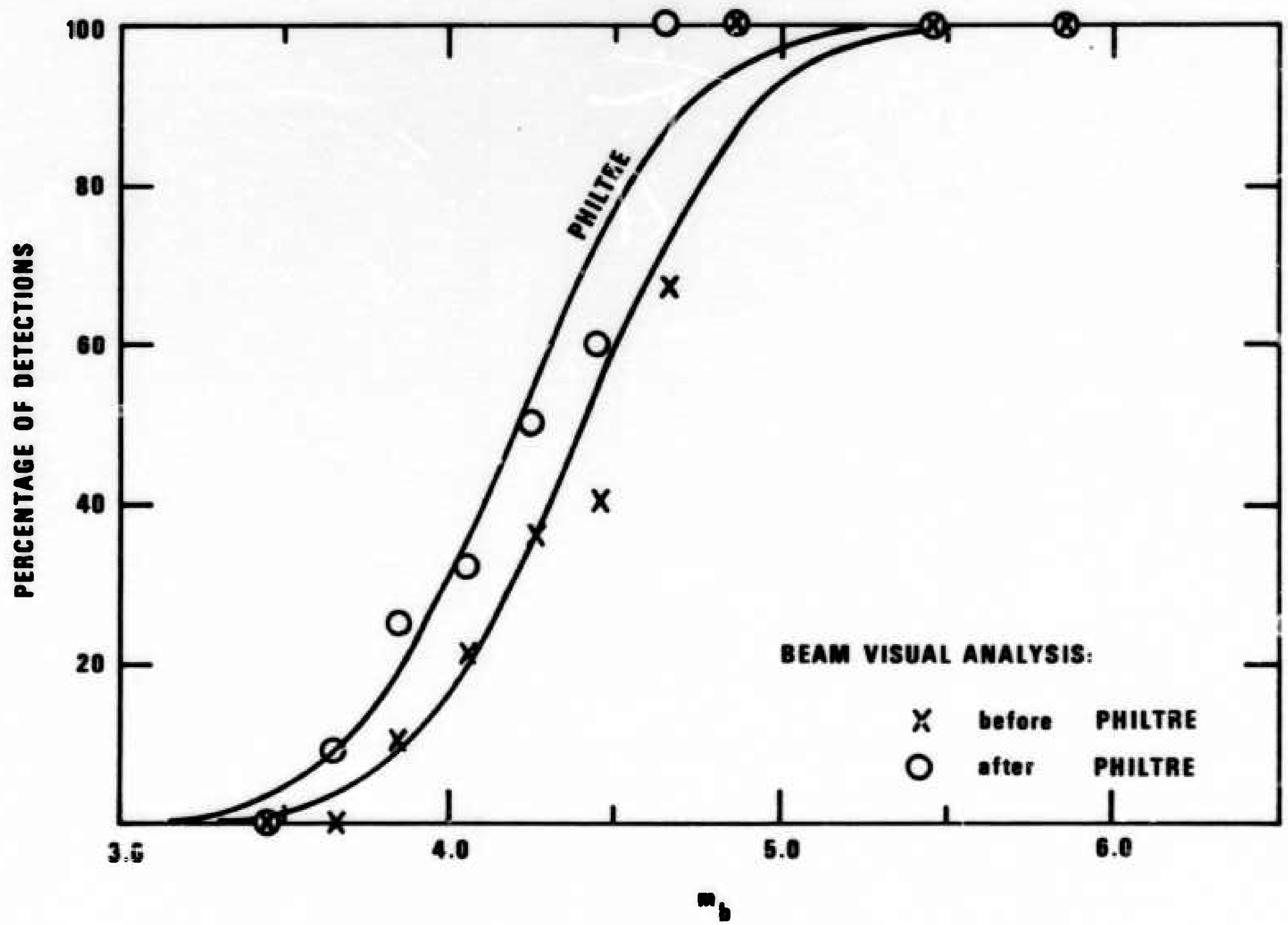

Figure 21. ALPA - % detections vs. m_b.

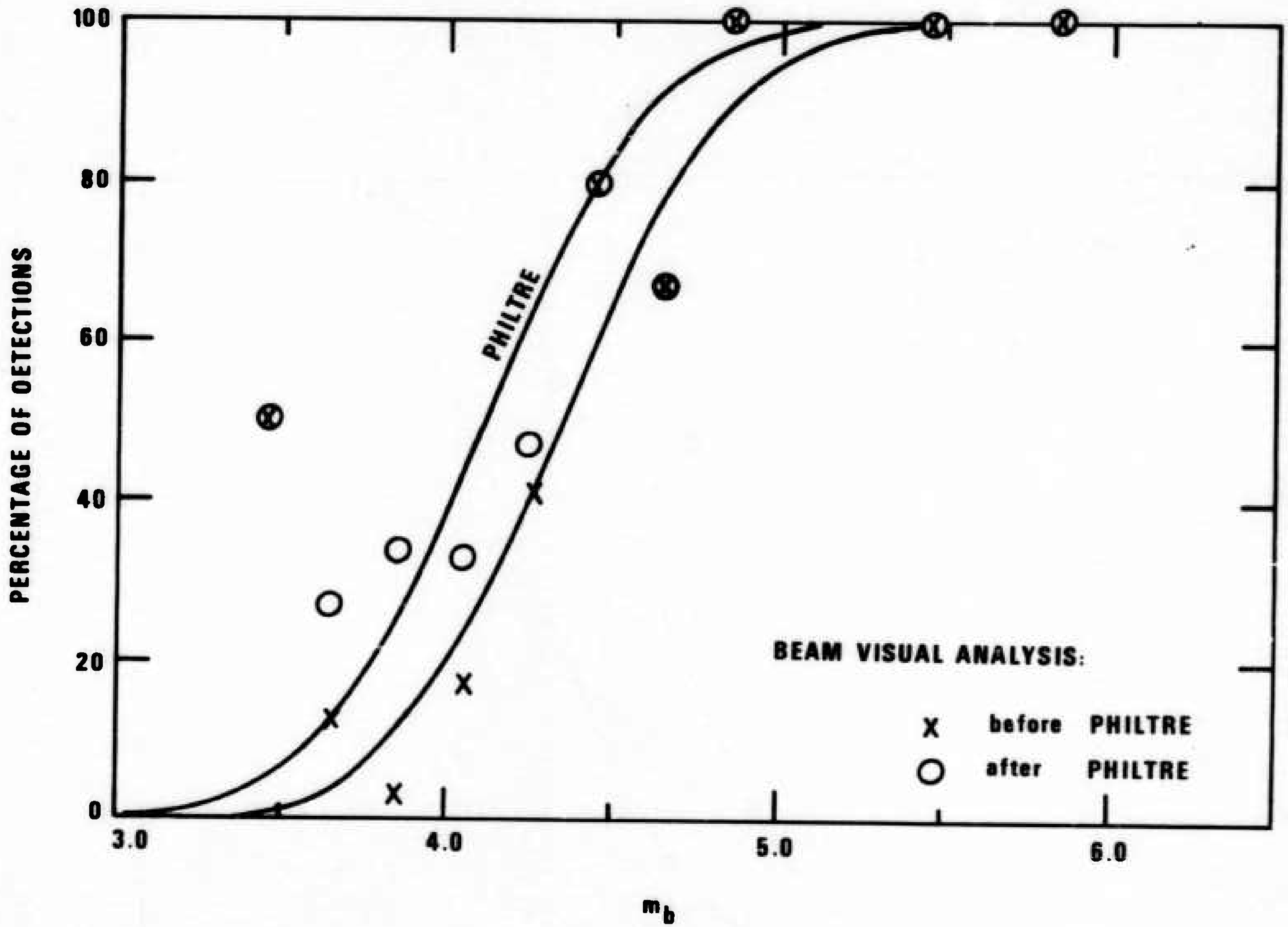

Figure 22. LASA - % detections vs. m_b.

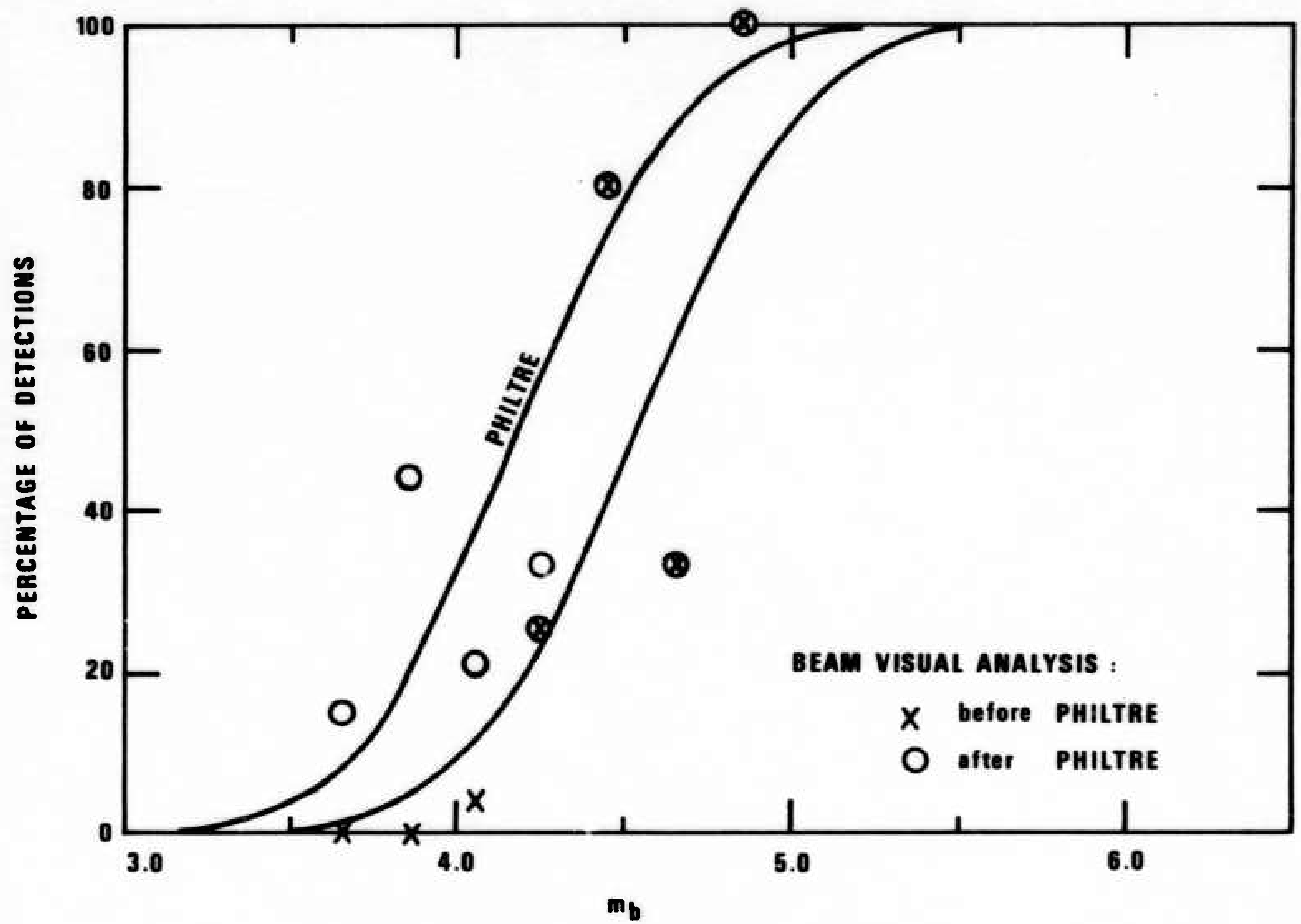

Figure 23. NORSAR - % detections vs. m_b.

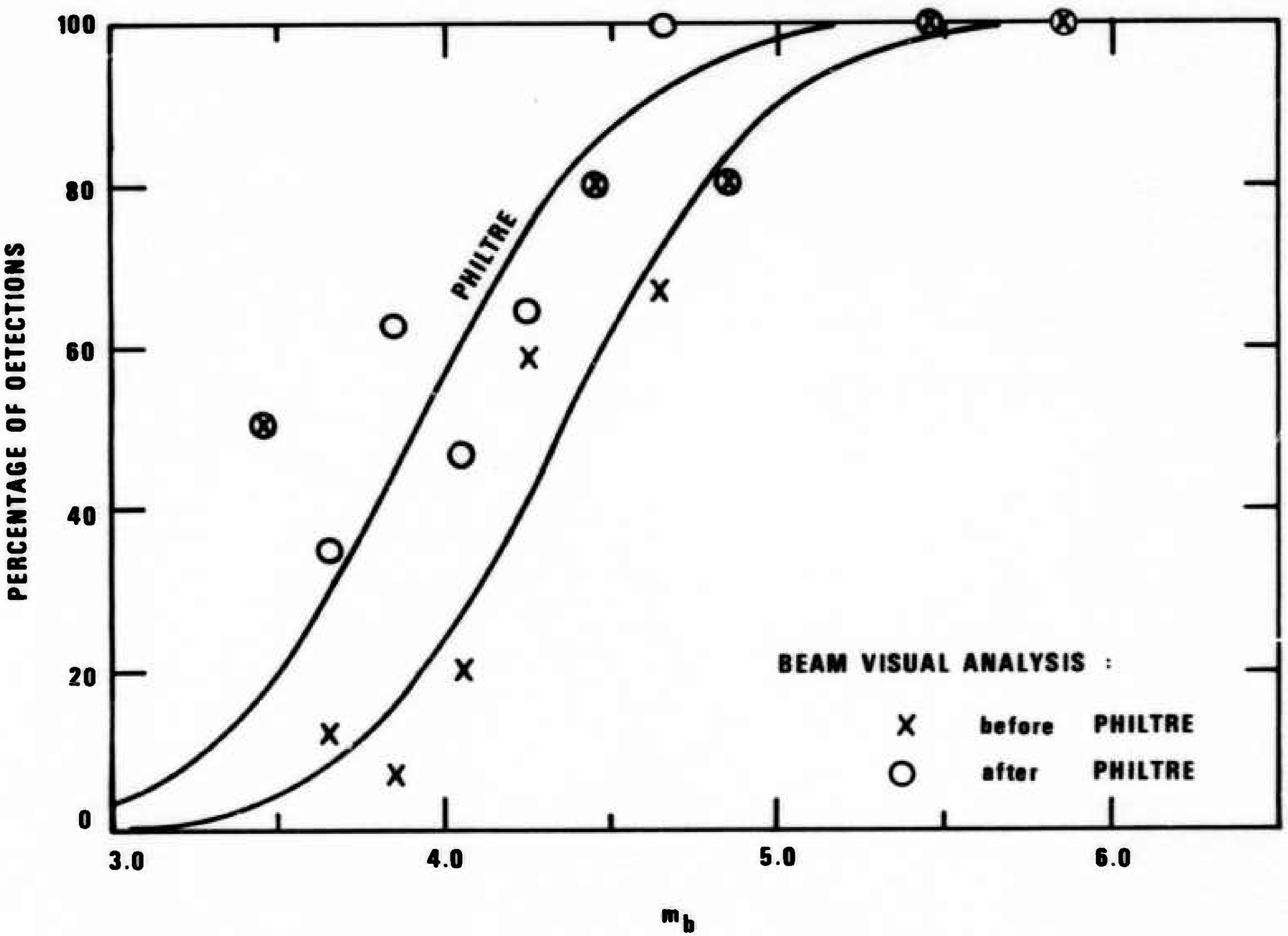

Figure 24. % detections by at least one array vs. m_b for a 3-array network.

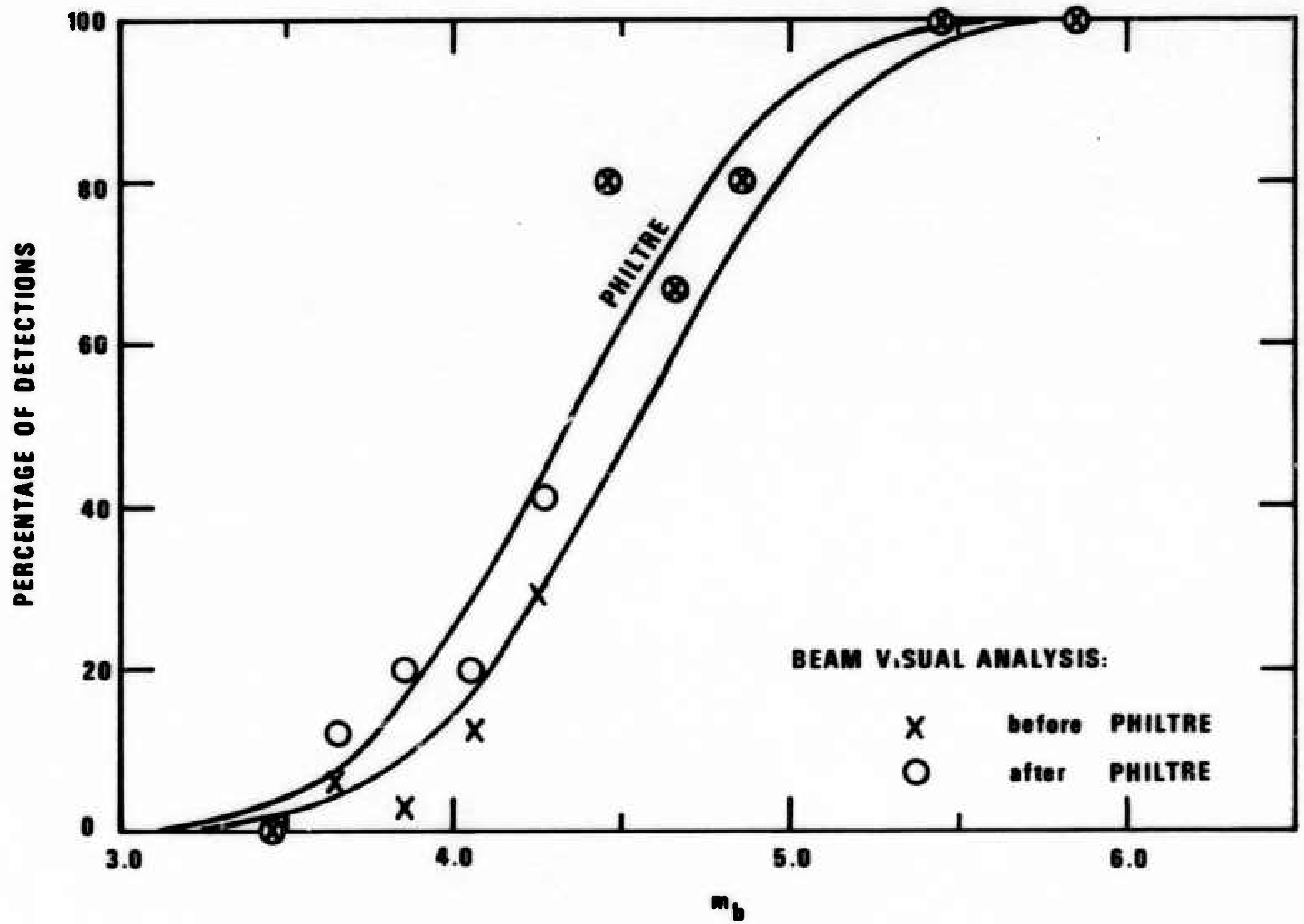

Figure 25. % detections by at least two arrays vs. m_b for a 3-array network.

TABLE IV

Fifty Percent m_b Detection Thresholds

	50% m_b Threshold From Original Beams	50% m_b Threshold From Filtered Beams	Improvement
ALPA	4.39	4.20	.19
LASA	4.34	4.11	.23
NORSAR	4.53	4.19	.34
At least 1 Detection in the 3-Array Network	4.35	3.92	.43
At least 2 Detections in the 3-Array Network	4.53	4.34	.19

and a 138 percent increase in the number of NORSAR detections. (Remember that no further detections were attained by simply bandpassing NORSAR data.) There are 94 percent more events detected by at least 1 array, 44 percent more events detected by at least 2 arrays and 67 percent more events detected by 3 arrays. Since the ALPA results are the poorest of the three arrays, detection rates for a 2-array network (LASA and NORSAR) were also calculated. There are 90 percent more events detected by at least 1 array and 73 percent more events detected by 2 arrays in this case. These detection results show that the thresholds are lowered, perhaps 0.2-0.3 magnitude unit (6 dB improvement). This is roughly as much as our results with signals buried in noise in an earlier section would indicate. We note that spikes in the ALPA beams and sudden jumps in the NORSAR beams produce strange effects in PHILTRE processing and were responsible for many spurious signals in the filtered output which hindered detection of the signal of interest. In one case PHILTRE was applied to an ALPA beam of a detected LR signal that contained several spikes; the filtered output showed no detection. The quality of the input data can thus effect the ability of PHILTRE to retrieve undetected LR phases; we feel that the results could have been significantly better, especially for ALPA, if the data input to PHILTRE had been good in every case. Lambert et al. (1973) report somewhat better results in a similar test of a PHILTRE-type processor on LPE data. Lane (1973) reports that the detection thresholds for beam data are unchanged after PHILTRE processing; however, that study used only ALPA beams, with which our results were the poorest of the three arrays.

Lambert, D., Prahl, S., and Strauss, A., 1973, Evaluation of the noise characteristics and the detection and discrimination capabilities of the very long-period experiment (VLPE) single stations and the VLPE Network, Texas Instruments Special Report No. 14.

Lane, S., 1973, Evaluation of an adpative three-component filter, Texas Instruments Special Report No. 15.

CONCLUSIONS

In this report PHILTRE showed a mean processor gain of roughly 14 dB for the LR phases at the visual detection threshold and about 17 dB at 5 dB above the visual detection threshold. The filter should be able to recover the LR phase down to a S/N input of about -6 dB, which is equivalent to other processors. Further research may show that the PHILTRE gain is additive to that from match filtering or maximum likelihood processing. Although PHILTRE deteriorates rapidly for S/N ratios below the visual detection threshold, its significant gain at the visual threshold should make many marginal detection decisions positive near the threshold.

PHILTRE is able to separate two signals if their azimuthal difference is greater than about 60 degrees and if at the same time the amplitude of the second signal is at least 20 percent of the amplitude of the first signal. Separation is possible for smaller azimuthal difference only if the signals have reasonably long non-overlapping parts.

The processor PHILTRE may be useful in recovering from ALPA, LASA, and NORSAR beams LR phases which are visually undetectable from events of low body-wave magnitude. In this study there was a 94 percent increase in the number of events detected by at least one of the three arrays and a lowering of the 50% threshold by 0.2-0.3 magnitude unit.

PHILTRE should be applied routinely to undetected signals, for it should recover a significant proportion of those signals which are below the noise level or which are interfered with. It is at least as important as bandpass filtering and match filtering in long-period signal detection because PHILTRE promises at least as much gain in S/N ratio and is easy to apply, although it requires more computation.

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